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LOAD CARRIAGE INDUCED ALTERATIONS OF PULMONARY FUNCTION

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ABSTRACT

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Load carriage systems supported by the trunk have been shown to decrease certain indices of pulmonary function. We investigated the hypothesis that these pulmonary function reductions are directly related to the backpack load carried due to the mechanical constraint it imposes on the thoracic cage. To investigate this hypothesis, 5 young males with no pulmonary disorders were tested while standing upright carrying well-fitted 0, 10 or 30 kg loaded U.S. Army ALICE backpacks. Forced vital capacity (FVC), forced expiratory volume (FEV₁) and 15 s maximal voluntary ventilation (MVV₁₅) were measured. With increasing load, FVC and FEV₁ progressively decreased reaching 6 and 6.7% decrements ($p < 0.05$), respectively, with the 30 kg load. The MVV₁₅ was decreased ($p < 0.05$) by about 8.4% with the 10 kg load, but did not demonstrate any further decrement with the 30 kg load. Analysis of flow-volume loops obtained with the 0 and 30 kg loads showed that the reduction of FVC was not associated with any decrement of peak inspiratory or expiratory flows. These results indicate a limitation on the ventilatory pump caused by load carriage which is directly related to the load carried and characteristic of restrictive disease of the respiratory system (reduced FVC and FEV₁ with no decrement in FEV₁/FVC).

Keywords: stress physiology; cardiovascular system; respiratory system; (K.T.)

INTRODUCTION

Load carriage systems are used as tools for a variety of industrial, military, and recreational situations. One of the most common types of load carriage systems used is backpacks. Although backpacks are used to carry a wide variety of loads, they have not been widely used in industrial settings. However, with the increased emphasis on protecting workers in hazardous environments,

there is for example, an increasing usage of backpack carried compressed air bottles to supply breathing masks. Many studies (Goldman and Iampietro, 1962; Legg and Mahanty, 1985; Pimental and Pandolf, 1979; Martin, 1986) have investigated the energy expenditures and biomechanics of carrying backpacks. However, there is very little information available on how the backpack's design and the mass carried will affect the pulmonary ventilation of the user. The backpack frame, harness and mass carried will oppose the expansion of the chest wall. These reductions may limit the pulmonary functions and therefore, would affect the ventilation during rest and exercise.

In a study by Legg and Mahanty (1985) comparing five modes of carrying a load close to the

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trunk, the subjects reported difficulty breathing while carrying a load equal to 35% of the subjects body weight. During the walk, the average oxygen uptake and minute ventilation were 1.15 l/min and 32.5 l/min, respectively, representing light work. Overall, the five load carriage systems reduced forced vital capacity (FVC) and forced expiratory volume in 1 s (FEV_1) by approximately 7% each and 15 s maximal voluntary ventilation (MVV_{15}) by about 13%. These results indicate a limitation on the ventilatory pump caused by load carriage which is characteristic of restrictive diseases of the respiratory system (reduced FVC and FEV_1 with no change in FEV_1/FVC).

Two reviews (Bye et al., 1983; Dempsey, 1986) of respiratory factors limiting exercise point out that except in normal subjects exercising in hypoxic or dense environments, or extremely fit individuals whose cardiovascular and metabolic transport systems are optimally developed, respiratory factors have not been shown to limit exercise in normal, average fit humans. However, it is possible that the respiratory pump may fail to provide sufficient ventilation to prevent arterial hypoxemia if its displacement is restricted or if the respiratory muscles cannot generate sufficient force to displace the chest wall. The study of Legg and Mahanty (1985) demonstrated that the displacement of the respiratory pump can be limited by the wear of the backpack.

Since the previous study (Legg and Mahanty, 1985) had used only one size load in the various load carriage systems they evaluated, we were interested in determining whether the load carriage induced decrements of pulmonary function are dependent upon the mass of the load carried.

Therefore, the present study assessed the pulmonary function response to carrying various loads in a backpack.

METHODS

Subjects

Five male soldiers volunteered to participate in the study. They received a physical examination and were informed of the purpose and procedures of the study, any known risks and their right to terminate participation at will without penalty. Each expressed understanding by signing a statement of informed consent.

Physiological measurements

Measurements of FVC and FEV_1 were obtained using a wet seal bell spirometer (Collins 9 L Spirometer). The subjects were instructed to inspire maximally to total lung capacity (TLC), then to exhale as forcefully, rapidly and as completely as possible to residual volume (RV). All tests were conducted in triplicate with the best effort recorded. Measurement of FVC and FEV_1 and calculation of FEV_1/FVC were done using standard methods (West, 1982). The MVV_{15} was determined using a nonrebreathing circuit connected to a low resistance dry gas meter (Singer, DTM-325). The subjects were instructed to breathe as hard and as fast as possible for 15 s. The minute ventilation was calculated by multiplying the total volume expired by four. All lung volumes were corrected to BTPS (Body Temperature Pressure Saturated).

TABLE 1

Physical characteristics of the subjects

Subject number	Age (year)	Weight (kg)	Height (cm)	FVC % predicted	FEV_1	MVV
1	25	62.5	165.5	111.6	102.9	119.2
2	19	72.9	180.5	95.3	90.0	77.6
3	19	72.6	175.5	95.4	88.0	90.0
4	19	77.8	183.0	69.8	75.6	86.1
5	19	68.7	171.5	93.2	96.3	110.7
Mean (\pm S.E.)	20 (1.2)	70.9 (2.5)	175.2 (3.1)	93.1 (6.7)	90.6 (4.6)	96.7 (7.8)

In several subjects, flow-volume curves were obtained using a pneumotachograph (Hewlett Packard, model 47304A) placed in line with the mouthpiece and inspiratory hose of the spirometer. The calibration of pneumotachograph was checked using a factory calibrated flow meter (Fischer & Porter). The inspiratory and expiratory flows were integrated to give inspiratory and expiratory volume, respectively. The volumes determined by integration of flow were compared with the volumes simultaneously measured by spirometry to ensure their accuracy. The subjects performed maximal inspiratory and expiratory efforts from RV and TLC, respectively.

Experimental design

All tests were conducted with the subjects wearing the U.S. Army Battle Dress Uniform. The subjects stood at rest while wearing, (1) no backpack, 0 load, (2) an ALL-Purpose lightweight Individual Carrying Equipment (ALICE) pack frame weighing 10 kg and (3) an ALICE pack frame weighing 30 kg. Lead bars strapped to the cargo shelf of each ALICE pack frame were used to increase the load carried. Each subject performed the pulmonary function tests under each of three conditions in a balanced randomized sequence. The subjects were given at least 30 s rest between forced expiration tests and 30 min between MVV_{15} tests. Two subjects performed flow-volume loop tests on a separate day. Only the 0 load and 30 kg load conditions were used during the flow-volume loop tests.

Statistical treatment

An analysis of variance (ANOVA) was used to statistically compare the ventilatory responses obtained during the three load carriage conditions. In the event that the repeated measures ANOVA revealed significant ($p < 0.05$) effects, Tukey's critical difference was calculated and used to locate significant differences between means.

RESULTS

Table 1 summarizes the physical characteristics of the test subjects. As a group, the subjects

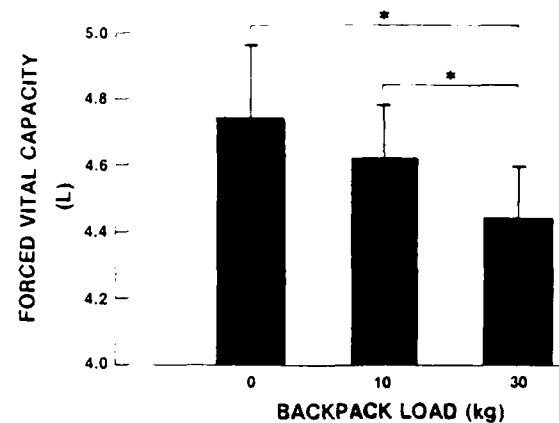


Fig. 1. FVC (BTPS) response to added backpack load. Group mean (\pm S.E.) is plotted. * indicates significant ($p < 0.05$) difference.

demonstrated normal pulmonary function when compared to predicted values for these measurements (Boren et al., 1966). During the control (0 load) tests, none of the subjects reported any discomfort performing these maximal effort ventilatory maneuvers. However, when wearing the loaded backpacks, during maximal inspirations all subjects indicated the sensation of chest wall (rib cage and abdomen) restriction.

Values of the group mean FVC obtained with the 3 load conditions are shown in Fig. 1. FVC was decreased as load increased. The decrement was not statistically significant ($p > 0.05$) with the

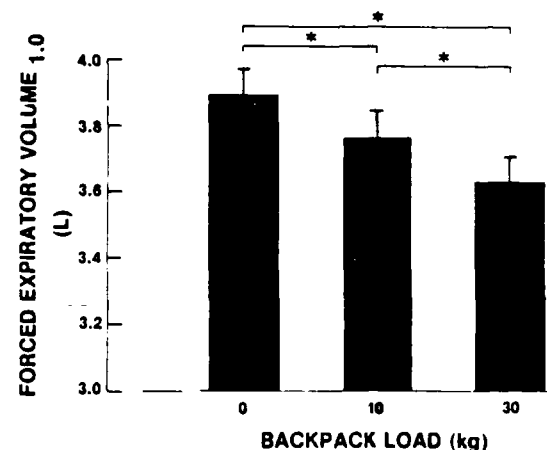


Fig. 2. FEV₁ (BTPS) response to added backpack load. Group mean (\pm S.E.) is plotted. * indicates significant ($p < 0.05$) difference.

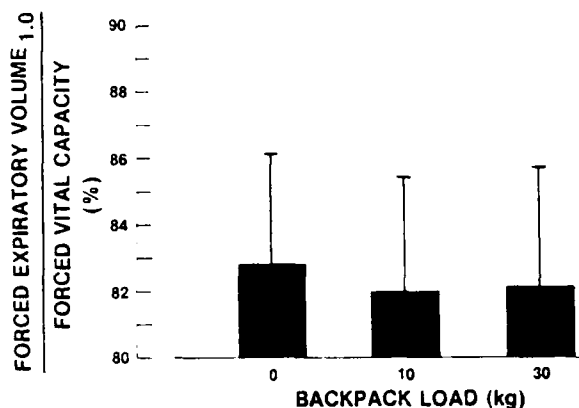


Fig. 3. FEV₁/FVC response to added backpack load.

10 kg load but was significant ($p < 0.05$) with the 30 kg load when compared to the 0 or 10 kg loads. The reductions were approximately proportional to the magnitude of the load. Wearing the 10 and 30 kg backpacks reduced FVC from its baseline value (0 kg load) by 2.5 and 6%, respectively.

The FEV₁ was also found to be reduced in approximate proportion with the backpack load (Fig. 2). The FEV₁ was significantly ($p < 0.05$) decreased by both the 10 and 30 kg loads when compared to the 0 load or each other. The FEV₁ was reduced by 3 and 6.7% from control by use of the 10 and 30 kg backpacks respectively. Given that both the FVC and FEV₁ demonstrated decrements roughly proportional to the load carried in the backpack, it followed that the ratio of FEV₁/FVC was not altered by increasing backpack load. This is shown in Fig. 3 where the FEV₁/FVC ratios were 82.8 ± 3.3 , 82.0 ± 3.4 and 82.1 ± 3.6 for the 0, 10 and 30 kg loads, respectively.

To further examine how the backpack altered the generation of maximal, voluntary vital capacity and flow maneuvers, flow-volume loops were measured in several subjects. Each flow-volume loop was generated by the subject first exhaling to RV then immediately performing a maximal inspiratory effort to TLC followed by a maximal expiratory effort back to RV. In Fig. 4 is shown one subject's flow-volume loops obtained with the 0 and 30 kg loads.

Comparison of the flow-volume loops obtained with the 0 and 30 kg loads showed the same

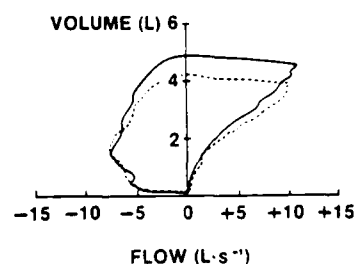


Fig. 4. Flow-volume loops (BTPS) during maximal voluntary inspiratory (– flow) and expiratory (+ flow) efforts. Solid line is test with 0 load, dotted line is with 30 kg load.

decrement in FVC as previously measured with the spirometer. Furthermore, analysis of the loops demonstrated that the reduction of FVC was not associated with any decrement of peak inspiratory or expiratory flows. Likewise, at intermediate and low lung volumes the effort-independent portion of the expiratory flow-volume curves were not altered by wearing the 30 kg backpack.

The results of the maximal voluntary ventilation tests are presented in the Fig. 5. The MVV₁₅ was significantly ($p < 0.05$) reduced wearing the 10 and 30 kg backpacks as compared to control. However, unlike the FVC and FEV₁ responses, the MVV₁₅ was similar for both the 10 and 30 kg backpack loads. The MVV₁₅ was reduced by 8.4 and 9.5% from control by use of the 10 and 30 kg backpacks, respectively.

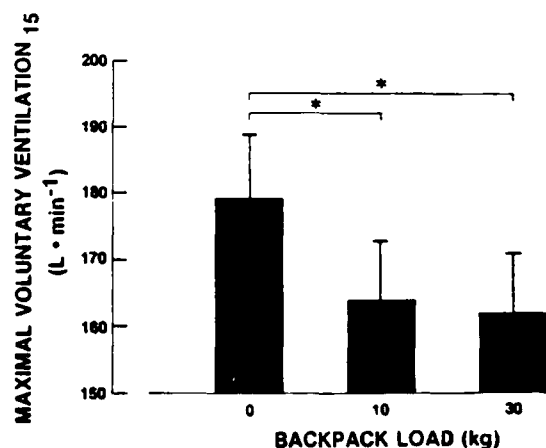


Fig. 5. MVV₁₅ (BTPS) response to added backpack load. Group mean (\pm S.E.) is plotted. * indicates significant ($p < 0.05$) difference.

DISCUSSION

We examined the effect that wearing a load carriage system has on pulmonary function. Our results indicate that several indices of pulmonary function are reduced in rough proportion to the load carried. With increasing backpack load, the FVC, FEV₁ and MVV₁₅ were reduced. Over the range of loads examined, there appears to be a linear decrease of FVC and FEV₁ with increasing backpack load, whereas the MVV₁₅ demonstrates a decrease by addition of a small load and no further decrement with increasing load. The latter finding that a load as small as 10 kg could produce a significant reduction in maximal ventilation is particularly striking. In most settings where backpacks are used, loads equal to or exceeding 10 kg are quite common.

It seems reasonable to expect that since many load carriage systems are most metabolically efficient when carried on the trunk (Datta and Ramanathan, 1971), these systems may alter pulmonary ventilation by interfering with movement of the chest wall. While numerous studies have investigated the effect of carrying loads on energy expenditure (Goldman and Iampietro, 1962; Legg and Mahanty, 1985; Pimental and Pandolf, 1979), walking patterns (Martin, 1986) and perception of exertion (Goslin and Rorke, 1986), only one previous study has examined alterations in pulmonary function (Legg and Mahanty, 1985). Legg and Mahanty (1985) reported that with five different load carriage systems carrying a load equal to 35% of the subject's body weight reduced FVC, FEV₁ and MVV₁₅. Our results with the 30 kg loaded backpack are similar to the findings of Legg and Mahanty (1985) using a similar backpack and frame. Their average reductions in FVC and FEV₁ were both about 5% whereas ours were about 7%. This difference is reasonable since our 30 kg load was about 42% of our subjects' body weight compared to their test load equal to 35% of body weight.

Legg and Mahanty (1985) found that the magnitude of the reductions were related to the style of load carriage system used. Generally, the greatest decrements in pulmonary function were associated with load carriage systems which covered the entire trunk (jacket, combination front and backpacks). The standard military backpack with

tubular metal frame produced the smallest decreases in pulmonary function. We chose the U.S. Army ALICE backpack and frame for testing because of its wide use in the army and the large range of loads which it is employed to carry. Given the results obtained by Legg and Mahanty (1985), our use of this style of load carriage system probably minimized the decrements in pulmonary function which we observed as a function of the load carried. Many U.S. Army special operations teams use internal frame or frameless rucksacks which have been shown (Legg and Mahanty, 1985) to cause greater pulmonary function decrements. Members of a Special Forces Team using an internal frame pack weighing about 45 kg with sternum strap have reported difficulty breathing due to chest restriction (personal communication). Taken together, the results of our study and the previous report by Legg and Mahanty (1985) indicate that the degree of pulmonary function decrement incurred by backpack wear is dependent upon both the load and the style of carriage system used.

The ventilatory system consists of the lungs, rib cage, diaphragm and abdomen, including the abdominal wall. The latter three components are called the chest wall. During normal, unloaded, resting breathing, the respiratory muscles are at rest at the end of expiration. The volume of air in the lungs at the end of a normal, relaxed expiration is referred to as the relaxation volume (V_{rel}). The lung volume occupied by the V_{rel} changes with posture and is determined by the establishment of an equilibrium between the elastic recoil of the lung, directed inward, and the elastic recoil of the chest wall, directed outward. The V_{rel} is composed of two lung volumes, the residual volume (RV) and the expiratory reserve volume (ERV). Wear of load carriage systems on the trunk probably decreases the V_{rel} by opposing the outward elastic recoil of the chest wall. It is obvious that use of a hip belt compresses the abdominal contents thus pushing the diaphragm upward into the thoracic cage and decreasing the ERV. The decreased V_{rel} may contribute to a sense of chest wall constriction even when the subject is between inspirations. Our results and others (Legg and Mahanty, 1985) indicate that use of load carriage systems decreases the vital capacity (VC). The VC, which changes with posture (Appel et al., 1986), is equal to the total lung capacity (TLC) minus the RV. It

is obvious that the RV would not be increased by wear of a backpack. Given that when carrying loads the subjects reported feelings of chest wall restriction, it would appear that the decrease of VC is due to a decrease of the TLC.

Use of load carriage systems on the trunk may oppose breathing in a manner similar to elastic loads. The pressure produced by an elastic load is directly related to the volume inspired. It is likely that while wearing a backpack, greater forces must be generated by the respiratory muscles during inspiration in order to overcome the forces produced by the load carriage system. Agostoni et al. (1978) have shown that in resting, conscious subjects respiratory frequency usually increases and the tidal volume decreases with elastic loading. These changes in the pattern of breathing may be the result of load compensating actions rising from intrinsic properties of the respiratory muscles, neural and chemical reflexes and behavioral components. At any given minute ventilation, wearing a backpack probably increases the work of breathing. Consequently, greater respiratory central drive and muscle tension must be developed to achieve a ventilatory rate which meets the metabolic demands. Killian et al. (1984) have reported that the sensation of breathlessness and effort are psychophysically the same. If so, then the use of load carriage systems may elicit unpleasant respiratory sensations as reported by Legg and Mahanty's (1985) subjects during moderate exercise. Whether the use of load carriage systems on the trunk could cause the development of respiratory muscle fatigue or in the absence of fatigue unpleasant respiratory sensations which limit work performance is yet to be determined. Finally, in many industrial and military tasks the combination of respiratory protective mask wear with backpack use may impose work performance limitations associated with the development of respiratory muscle fatigue or dyspnea.

The current study and the investigation by Legg and Mahanty (1985) report decrements of MVV_{15} which are further evidence that wear of load carriage systems alter the pattern of breathing at least during high levels of ventilation. During the performance of the MVV_{15} , normal subjects with unopposed ventilation generally use a tidal volume of about 30% of VC with equal inspiratory and expiratory durations (Mead and Agostoni, 1964).

Given that the wear of a backpack reduced FVC by about 7%, the tidal volumes achieved during the MVV_{15} maneuvers should not have been limited by the decrease of FVC. Likewise, the flow-volume loops with and without the backpack did not indicate a decrease in the ability to develop maximal inspiratory and expiratory air flows. However, if the MVV maneuver was forced to be done at a lower lung volume where lower maximal expiratory flows were available, then a decreased MVV would be expected. Without analysis of the pattern of breathing during the MVV_{15} maneuvers, the changes in volume or timing which resulted in the decreased MVV_{15} cannot be determined.

Decreases in vital capacity and maximum flow rate are criteria for restrictive diseases of the respiratory system. Furthermore, inspiration is limited by the reduced compliance of the lung or chest wall, or weakness of the inspiratory muscles (West, 1982). Use of load carriage systems on the trunk produces some of the pulmonary dysfunctions seen in restrictive respiratory diseases. However, most restrictive diseases involve changes in the interstitium which disrupts alveolar-capillary gas exchange as well as respiratory mechanics (West, 1982). Consequently, patients with interstitial lung disease developed arterial hypoxemia during exercise despite normal minute ventilations (Lourenco et al., 1965). The use of load carriage systems may limit exercise only if sufficient ventilation cannot be achieved or maintained to prevent arterial oxygen desaturation or dyspnea or hypercapnia. Further studies need to determine the effect carrying a backpack has on the pattern and mechanics of breathing during rest and sustained aerobic exercise. These factors should be considered when purchasing or designing load carriage systems.

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NOTE

The views, opinions and/or findings in this report are those of the authors and should not be construed as official department of the Army position, policy or decision unless so designated by other official documentation. Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on Use of Volunteers in Research.

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